Astronomy & Astrophysics manuscript no. paper˙2column
February 11, 2015

Letter to the Editor

High redshift AGNs and HI reionisation: limits from the unresolved X-ray background

Francesco Haardt[1,2] and Ruben Salvaterra[3]

[1] DiSAT, Università dell'Insubria, Via Valleggio 11, I-22100 Como, Italy
[2] INFN, Sezione di Milano-Bicocca, Piazza delle Scienze 3, I-20123 Milano, Italy
[3] INAF, IASF Milano, via E. Bassini 15, I-20133 Milano, Italy

Received/Accepted

ABSTRACT

The rapidly declining population of bright quasars at $z \gtrsim 3$ appears to make an increasingly small contribution to the ionising background at the H I Lyman limit. It is then generally though that massive stars in (pre-)galactic systems may provide the additional ionising flux needed to complete H I reionisation by $z \gtrsim 6$. A galaxy dominated background, however, may require that the escape fraction of Lyman continuum radiation from high redshift galaxies is as high as 10%, a value somewhat at odds with (admittedly scarce) observational constraints. High escape fractions from dwarf galaxies have been advocated, or, alternatively, a so-far undetected (or barely detected) population of unobscured, high-redshift faint AGNs. Here we question the latter hypothesis, and show that such sources, to be consistent with the measured level of the unresolved X-ray background at $z = 0$, can provide a fraction of the H II filling factor not larger than 13% by $z \simeq 6$. The fraction rises to $\lesssim 27\%$ in the somewhat extreme case of a constant comoving redshift evolution of the AGN emissivity. This still calls for a mean escape fraction of ionising photons from high-z galaxies $\gtrsim 10\%$.

Key words. cosmology: observations – X–ray: diffuse background – galaxies: active

1. Introduction

The reionisation of the all-pervading intergalactic medium (IGM) is a landmark event in the history of the Universe. Studies of the so-called Gunn-Peterson absorption in the spectra of distant quasars show that hydrogen was already highly ionised out to redshift $z \sim 6$ (e.g., Songaila 2004; Fan et al. 2006), while CMB polarisation data constrain the redshift of a sudden reionisation event to be significantly higher, $z \sim 10$ (Jarosik et al. 2011; Hinshaw et al. 2013).

Most of our understanding of IGM physics, and its implication for galaxy formation and metal enrichment, depends critically on the properties of the cosmic ionising background. While it is generally thought that the gas is kept ionised by the integrated UV emission from active galactic nuclei (AGNs) and star-forming galaxies (Miralda-Escude & Ostriker 1990; Haardt & Madau 1996), the relative contributions of these sources as a function of cosmic time are poorly known.

At $z \gtrsim 3$, the declining population of bright quasars appears to make an increasingly small contribution to the ionising radiation background at the H I Lyman limit. It was then suggested that massive stars in galactic systems may provide the additional ionising flux needed at early times (e.g. Madau et al. 1999; Gnedin 2000; Wyithe & Loeb 2003; Meiksin 2005; Trac & Cen 2007; Faucher-Giguère et al. 2008; Gilmore et al. 2009; Robertson et al. 2010). However, leaking Lyman continuum radiation from bright galaxies seem to be modest (see, e.g., Vanzella et al. 2010), and it has been therefore argued that dwarf galaxies (with virial mass below $\sim 10^9$ $M_\odot$) may produce the dominant contribution to the H I ionising UV background (e.g., Robertson & Ellis 2012).

Alternative to invoking a major contribution to reionisation from dwarf(ish) galaxies is the possibility that the AGN emissivity at $z \gtrsim 4$ is indeed much larger than generally thought. Indications along such line have been reported by several groups (Glikman et al. 2011; Civano et al. 2011; Fiore et al. 2012), though it is fair to say that results seem not so univocal (see, e.g., Masters et al. 2012). Very recently, Giallongo et al. (2015) found 22 AGN candidates at $z \gtrsim 4$ in the Candel/GOOD-S/Chandra Deep Field South field, suggestive of a prominent contribution of AGNs to the ionising background in the range $4 \lesssim z \lesssim 6.5$. The resulting H I photoionisation rate is indeed consistent with various estimates at the same redshifts, based on both the flux-decrement and proximity effect techniques (Becker et al. 2007; Calverley et al. 2011).

The high redshift population of AGNs should leave an imprint in the observed cosmic X-ray background (XRB). *Chandra* deep observations resolved the XRB into discrete sources at a level of $80-90\%$ over the entire bandwidth ($0.5-2$ keV), with only a fraction $\sim 1\%$ of the signal arising from sources located at $z \gtrsim 4$ (Xue et al. 2011). Moretti et al. (2012) exploited the very low instrumental noise of the *Swift* XRT to measure the still unresolved XRB spectrum at the highest accuracy. In Salvaterra et al. (2012) we used such measures to place upper limits on the cosmic accretion history of massive black holes. An obvious caveat to our conclusions is the possible existence of a large population of severely obscured ($\log N_H \gtrsim 25$)accreting black holes, hence not glowing in the X-rays. Unless advocating a very peculiar UV-to-X-ray spectral energy distribution, such caveat would not apply if the unresolved AGN population does contribute significantly to the ionisation background. The assessment of the contribution to the XRB of such UV-emitting AGNs is precisely the goal of this *Letter*. Specifically, we will translate the Moretti et al. (2012) upper limits to the unresolved XRB into upper limits on the possible contribution of high-

redshift, unobscured faint AGNs to H I reionisation. A similar analysis was proposed by Dijkstra et al. (2004), Salvaterra et al. (2005, 2007), and McQuinn (2012), with conflicting results. Here we use the most updated limits on the XRB and adopt a $(h, \Omega_m, \Omega_\Lambda) = (0.7, 0.3, 0.7)$ cosmology.

2. Methodology

Assuming an AGN comoving X-ray specific emissivity $\propto E^{-\alpha_x}(1+z)^{-\gamma}$, the XRB at observed energy E_0 due to sources located at redshift $z \geq z_x$ is:

$$J_{E_0}(\geq z_x) = \frac{c}{4\pi} \int_{z_x}^{\infty} dz \left|\frac{dt}{dz}\right| \epsilon_{2\mathrm{keV}} \left(\frac{E}{E_{2\mathrm{keV}}}\right)^{-\alpha_x} (1+z)^{-\gamma}, \qquad (1)$$

where $E = E_0(1+z)$. We now relate the specific emissivity at 2 keV, $\epsilon_{2\mathrm{keV}}$, to that at 912Å, i,.e., $\epsilon_{2\mathrm{keV}} = K\epsilon_{912\text{Å}}$, where the "$K$-correction" normalisation reads

$$K = \left(\frac{1300\text{Å}}{912\text{Å}}\right)^{\alpha_{\mathrm{fuv}}} \left(\frac{2500\text{Å}}{1300\text{Å}}\right)^{\alpha_{\mathrm{uv}}} \left(\frac{E_{2\mathrm{keV}}}{E_{2500\text{Å}}}\right)^{-\alpha_{\mathrm{ox}}}. \qquad (2)$$

Here α_{ox} is the optical-to-X-rays spectral index, defined from the specific emissivity at 2 keV and at 2500 Å, $\alpha_{\mathrm{ox}} \equiv -0.384 \log(\epsilon_{2\mathrm{keV}}/\epsilon_{2500\text{Å}})$. In writing eq. 2 we followed the piecewise UV AGN spectral energy distribution as described in Haardt & Madau (2012). Now the r.h.s. integral in eq. 1 is easily solved, and the obtained $J_{E_0}(\geq z_x)$ constrained to be not larger than the observational upper limit $J_{E_0}^{\mathrm{obs}}$. This in turn gives the maximum value of $\epsilon_{912\text{Å}}$ consistent with the limits on the unresolved XRB:

$$\epsilon_{912\text{Å}}(z) \leq \frac{4\pi H_0 \Omega_m^{1/2}}{c\,K\,R_{II}}\, \eta (1+z_x)^{\eta} (1+z)^{-\gamma} J_{E_0}^{\mathrm{obs}}, \qquad (3)$$

where we neglected the energy density of the cosmological constant (we are interested in the redshift regime $z \gg z_{m\Lambda} \simeq 0.33$). We set $\eta \equiv (\gamma + \alpha_x + 3/2)$ and the term $R_{II} \geq 1$ is meant to account for the contribution of obscured AGNs at $z \geq z_X$ to the XRB observed at energy E_0.

It is now straightforward to translate the above limit into a limit on reionisation. The volume filling factor of H II regions Q_{HII} is the solution of the following differential equation (see Madau et al. 1999):

$$\frac{dQ_{\mathrm{HII}}}{dt} = \frac{\dot{n}}{n_0} - \frac{Q_{\mathrm{HII}}}{t_{\mathrm{rec}}}, \qquad (4)$$

where n_0 is the cosmic hydrogen mean density, and $\dot{n}(z) = \epsilon_{912\text{Å}}(z)/(h_p \alpha_{\mathrm{fuv}})$ the photon emission rate (h_p is the Planck constant, and the FUV emissivity is $\propto \nu^{-\alpha_{\mathrm{fuv}}}$). The H II recombination time t_{rec} is computed as in Haardt & Madau (2012).

3. Observational Parameters

The upper limits given by eq. 3 and eq. 4 depend upon a number of parameters which need to be observationally constrained. In this section we discuss the choice we make for each of them.

Unresolved XRB. The unresolved XRB shows a very hard spectrum, suggesting that most (if not all) of the flux comes from low-z obscured AGNs. Indeed, Moretti et al. (2012), by adopting the XRB synthesis model of Gilli et al. (2007), derived a stringent limit $J_{E_0}^{\mathrm{obs}} \leq 1.9 \times 10^{-27}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1} at $E_0 = 1.5$ keV once accounting for absorbed AGNs at $z \lesssim 5$ whose fluxes lie below the *Chandra* limit. Yet, the synthesis model falls short at $E_0 \gtrsim 3$ keV, suggesting the possible existence of a population of Compton thick AGNs at intermediate redshifts.

UV and X-ray spectral indices. As already stated, we use the very same parametrisation of Haardt & Madau (2012), adopting for the UV slope $\alpha_{\mathrm{uv}} = 0.44$ ($\lambda > 1300$ Å, Vanden Berk et al. (2001)), and $\alpha_{\mathrm{fuv}} = 1.57$ in the FUV range ($\lambda < 1300$ Å, Telfer et al. (2002)). Concerning the X-ray spectrum, we notice that most of the contribution to the XRB at $E_0 = 1.5$ keV is expected from source located just above $z \simeq 5$, i.e., from photons emitted at rest-frame energy $\simeq 10$ keV. In this energy range unobscured AGNs exhibit a power-law spectrum with index $\alpha_x \simeq 0.8$, as a combination of the intrinsic continuum and of the Compton reflection bump (see, e.g., Ueda et al. (2014)). In our analysis we then take $\alpha_x = 0.8$. From eq. 2 it is apparent how the exact values of the UV and X-ray spectral indices will affect our conclusions only marginally.

Optical-to-X-ray spectral index. The value of α_{ox} has a major impact on our estimate of Q_{HII} since $(E_{2\mathrm{keV}}/E_{2500\text{Å}}) \simeq 403$. The study of the correlation between X-ray and UV luminosities has been the subject of many works on both optically selected and X-ray selected AGNs. Among others, Steffen et al. (2006) found a significant correlation between α_{ox} and the monochromatic luminosities at 2500 Å (i.e., $L_{2500\text{Å}} \propto L_{2\mathrm{keV}}^{\beta}$, with $\beta > 1$) in a sample of 333 optically selected AGNs. No significant correlation of α_{ox} with redshift was reported. Lusso et al. (2010) analysed a sample of 545 X-ray selected Type I AGNs from the XMM-COSMOS survey, finding again a correlation between α_{ox} and $L_{2500\text{Å}}$. The mean value of α_{ox} for the full sample was 1.37 with a dispersion around the mean of 0.18. Marchese et al. (2012) also reported a highly significant correlation between α_{ox} and the UV luminosity in a sample of 195 X-ray selected Type I bright AGNs, basically confirming the Lusso et al. (2010) results. In our investigation the supposedly unaccounted population of AGNs responsible of H I reionisation must necessarily resides in the very faint-end of the UV luminosity function. According to the literature cited above, this would imply a value of α_{ox} on the lowest side of the distribution, though it must be considered that the redshift range of interest here is basically unexplored at X-ray wavelengths. Given that, we adopt a fiducial value $\alpha_{\mathrm{ox}} = 1.35$. We are confident that, if the observed correlation between $L_{2500\text{Å}}$ and α_{ox} holds at very high redshifts, such choice is conservative, hence strengthening our conclusions.

Redshift evolution. The evolution of the AGN space density at high redshifts has been subject of several revisions in the last decade, mainly because of the dearth of data at $z \gtrsim 4$. As an example, Ueda et al. (2003) adopted, for very luminous sources, an evolution factor $\propto (1+z)^{-\gamma}$ with $\gamma = 1.5$ above $z = 1.9$, while for fainter AGNs the turn over occurs at increasingly lower redshift. Silverman et al. (2008) found a much sharper decline, $\gamma = 3.27$, similar to that derived in studies of optically selected QSOs. Recently, Hiroi et al. (2012) claimed an even stronger decline at $z \gtrsim 3$, $\gamma = 6.2$, a value adopted by Ueda et al. (2014) in the most recent and updated study of the hard X-ray LF. The situation is somewhat more confusing in the optical-UV band. While different groups agreed on the faint-end slope of the LF, $\simeq 1.7$, they sorted out quite different absolute space densities. Specifically, Glikman et al. (2011) claim roughly a factor four more sources at $z \gtrsim 3$ compared to Ikeda et al. (2011). More recently, Masters et al. (2012) found a decrease by a factor of four in the number density of faint QSOs in COSMOS between $z \sim 3.2$ and $z \sim 4$, supporting the results of Ikeda et al. (2011). Overall, the results from Masters et al. (2012) suggest a similar evolution of the UV and X-ray LFs at $z \gtrsim 3$. However,

a large normalisation of the UV LF, basically consistent with Glikman et al. (2011) though at higher redshifts ($z \simeq 5-6$) and fainter UV magnitudes, was recently claimed (Giallongo et al. 2015). Given these uncertainties, we will assume a redshift evolution of the emissivity as sharp as $\gamma = 6.2$ in both the X-ray and UV bands, but we will also show results for the somewhat extreme case of a constant comoving emissivity ($\gamma = 0$).

Obscured sources. The parameter R_{II} in eq. 3 is meant to account for the contribution to the XRB given by sources obscured in the optical band, thus not contributing to the ionising background. Such contribution could be relevant since photons observed at $E_0 = 1.5$ keV are emitted, by $z \gtrsim 5$ AGNs, at rest frame energies $\gtrsim 10$ keV, where the emission of absorbed AGNs is anyway relevant. We implemented the X-ray LF of Ueda et al. (2014), and found that $J_{E_0}(\geq z_x)$ (with $E_0 = 1.5$ keV and $z_x = 5$) is almost evenly divided between objects with $\log N_H < 22$ and objects with $\log N_H > 22$, which would give $R_{II} \simeq 2$. However, it is not simple to determine above which X-ray determined equivalent hydrogen column density N_H sources are severely obscured in the optical-UV band. In their study, Masters et al. (2012) found that $\sim 75\%$ of X-ray bright AGNs at $z \sim 3-4$ are indeed optically obscured. Taken at face value, this would imply $R_{II} \simeq 4$. Finally it is worth noticing that at lower redshifts ($z \lesssim 3$) the incidence of obscured AGNs is strongly anti-correlated with X-ray luminosity (Merloni et al. 2014). Provided that the trend is similar at earlier epochs, this very fact points toward a high R_{II} correction factor. In our fiducial model we then assume $R_{II} = 4$.

Lower redshift of unresolved XRB. In our analysis, the limiting redshift z_x plays an important role, as it sets the minimum redshift of the unaccounted AGN population we are testing. Clearly, such population must give a contribution to the XRB not exceeding the measured unresolved fraction. Specifically, the upper limits to the unresolved XRB given by Moretti et al. (2012) were obtained subtracting to the total XRB all sources listed in the 4Ms-Chandra catalog (Xue et al. 2011), which basically contains no AGNs with $z \gtrsim 5$. As and example, among the 6 AGN candidates at $z \gtrsim 5$ found by Giallongo et al. (2015), only 2 are in the Xue et al. (2011) catalog. Should the unresolved XRB arise from high-z AGNs, it must necessary come from $z \gtrsim 5$ sources unless they own a very peculiar redshift distribution. Given that, we assume $z_x = 5$ as the lower limiting redshift in our study.

To summarise, our benchmark model adopts: $\alpha_{\rm fuv} = 1.57$, $\alpha_{\rm uv} = 0.44$, $\alpha_x = 0.8$, $\alpha_{\rm ox} = 1.35$, $\gamma = 6.2$, $R_{II} = 4$, $z_x = 5$, and the XRB limit $J^{\rm obs}_{1.5{\rm keV}} \leq 1.9 \times 10^{-27}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}.

4. Results

Fig. 1 shows $\epsilon_{912\text{Å}}$ given by eq. 3. The emissivity at the Lyman limit is a most interesting quantity, as it can be compared to diverse observational estimates existing in literature. Our benchmark case is shown as the red solid line starting from $z = 5$. Our limit is compared to the recent values of Giallongo et al. (2015) and to the values reported by Masters et al. (2012) (shown as black data points and open triangles, respectively). An assessment of the reasons behind the discrepancy between these different results is beyond the scope of this letter. Still, taking the Giallongo et al. (2015) ionising emissivity at face value, we must conclude that the associated AGNs basically saturate the observed XRB, as apparent from Fig. 1.

We also compare our estimate of $\epsilon_{912\text{Å}}$ with the "minimum reionisation model" of Haardt & Madau (2012). In Fig. 1 the overall Lyman limit emissivity of Haardt & Madau (2012) is

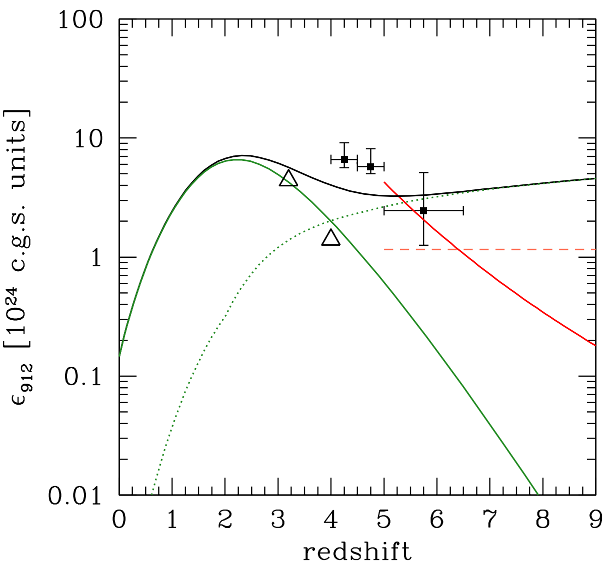

Fig. 1. The maximum emissivity at the H I Lyman limit vs. redshift. The red solid curve at $z \geq 5$ is our benchmark case, consistent with the XRB limit $J^{\rm obs}_{1.5{\rm keV}} \leq 1.9 \times 10^{-27}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}. Such value accounts for sources at $z \lesssim 5$ below the Chandra flux limit, estimated from the Gilli et al. (2007) XRB synthesis model. The dashed line shows the extreme case of a constant comoving redshift evolution of the AGN emissivity. The black line is the emissivity employed in the UV background model of Haardt & Madau (2012), with galaxies (dotted green line) and AGNs (solid green line) shown separately. The black data points are the AGN emissivity as estimated by Giallongo et al. (2015), while open triangles are data from Masters et al. (2012).

shown as a black solid line, along with the separate contribution of AGNs (green solid line) and star forming galaxies (green dotted line). The AGN emissivity closely fits the results by Hopkins et al. (2007), while for galaxies Haardt & Madau (2012) assumed that the fraction of Lyman continuum photons leaking into the IGM is a strong increasing function of redshift. Such model reionises H I by $z \simeq 6.7$ and He II by $z \simeq 2.8$. Though our estimate benchmark emissivity at $z \simeq 5-6$ is similar to the Haardt & Madau (2012) model, the approximatively constant comoving behaviour of the latter compared to the steep decline we adopt here leads to the different outcome in terms of reionisation (see next). For such reason we tested the somewhat extreme case of a constant comoving emissivity, shown as a dashed line in Fig. 1. The resulting maximum emissivity is lower than the Haardt & Madau (2012) reionisation model by a factor of $\simeq 4$ at high-z.

In Fig. 2 we show the resulting volume fraction occupied by H II regions (eq. 4). Our benchmark case allows for a fraction $\lesssim 13\%$ of the IGM to be ionised by AGNs by $z \gtrsim 6$, showing that AGNs alone can not reionise the Universe. We checked that this conclusion holds in spite of the uncertainties of the parameters. $Q_{\rm HII} = 1$ at $z = 6$ can be reached only for $\alpha_{\rm ox} \gtrsim 1.7$, or $\alpha_{\rm ox} \gtrsim 1.5$ assuming $R_{II} \simeq 1$ (i.e., no obscured sources). Such figures seem to be unlikely when compared to available data. Finally, the constant comoving case (dashed line) produces a more extended reionisation history, still it can only account for $\lesssim 27\%$ of the

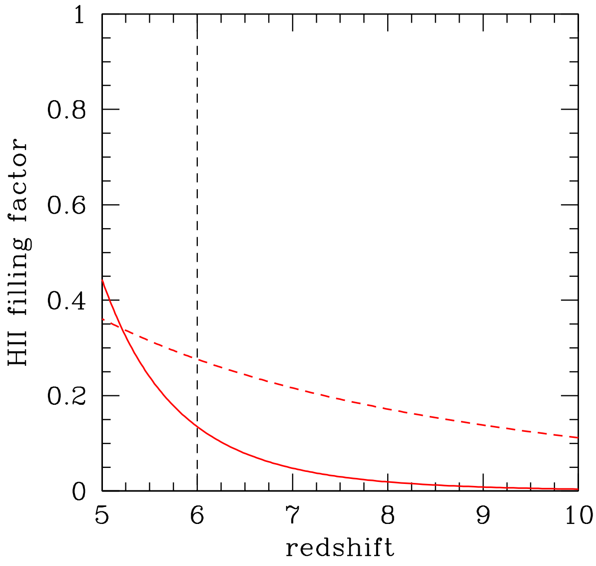

Fig. 2. Maximum volume filling factor of H II vs. redshift. Curves as in Fig. 1. The dashed vertical line marks a fiducial reionisation redshift, $z = 6$. In our benchmark case the contribution to H II reionisation from AGNs is below 13%.

ionised volume at $z \gtrsim 6$. In this case, reionisation by $z \gtrsim 6$ requires a mean escape fraction from star forming galaxies $\gtrsim$ 10%.

It is interesting to note that the benchmark case (as well as the AGNs observed by Giallongo et al. (2015)) would produce a H I ionisation rate consistent with $z \simeq 5 - 6$ data (e.g., Wyithe & Bolton 2011; Calverley et al. 2011), still it falls short in reionsing the IGM at $z \gtrsim 6$ (Fig. 2). In other words, matching the observed level of the ionising background just below the ionisation redshift does not guarantee that a particular model is actually consistent with the entire reionisation history of the IGM.

A final comments concerns He II reionisation. Though a detailed assessment of such process is beyond the scope of this Letter, an AGN dominated background would certainly lead to an extended reionisation epoch. This may agree with the recent claiming of Worseck et al. (2014), but it may be in conflict with the sharp increase of the IGM temperature at mean cosmic density observed in the range $2 \lesssim z \lesssim 4$ (Schaye et al. 2000; Becker et al. 2011; Bolton et al. 2012, 2014; Boera et al. 2014).

5. Conclusions

Under reasonable assumptions, we have shown that a population of unobscured, UV emitting AGNs at $z \gtrsim 5$ if leading H I reionisation would exceed observational constraints derived from the unresolved fraction of the X-ray background. Even a constant comoving emissivity at high-z would not be enough to produce an AGN dominated ionising background. AGNs can account for a fraction of the ionising photon budget $\lesssim$ 13%, calling for a dominant contribution from star forming galaxies. Given the observational constraints (e.g., Bouwens et al. 2011) on the galaxy population at high-z, this in turns requires a large mean escape fraction ($\gtrsim$ 10%).

Acknowledgements. We thank A. Comastri, P. Madau, A. Moretti for many fruitful discussions, and E. Giallongo for allowing us to use their results before publication.

References

Becker, G. D., Bolton, J. S., Haehnelt, M. G., & Sargent, W. L. W. 2011, MNRAS, 410, 1096
Becker, G. D., Rauch, M., & Sargent, W. L. W. 2007, ApJ, 662, 72
Boera, E., Murphy, M. T., Becker, G. D., & Bolton, J. S. 2014, MNRAS, 441, 1916
Bolton, J. S., Becker, G. D., Haehnelt, M. G., & Viel, M. 2014, MNRAS, 438, 2499
Bolton, J. S., Becker, G. D., Raskutti, S., et al. 2012, MNRAS, 419, 2880
Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2011, ApJ, 737, 90
Calverley, A. P., Becker, G. D., Haehnelt, M. G., & Bolton, J. S. 2011, MNRAS, 412, 2543
Civano, F., Brusa, M., Comastri, A., et al. 2011, ApJ, 741, 91
Dijkstra, M., Haiman, Z., & Loeb, A. 2004, ApJ, 613, 646
Fan, X., Carilli, C. L., & Keating, B. 2006, ARA&A, 44, 415
Faucher-Giguère, C.-A., Lidz, A., Hernquist, L., & Zaldarriaga, M. 2008, ApJ, 682, L9
Fiore, F., Puccetti, S., Grazian, A., et al. 2012, A&A, 537, A16
Giallongo, E., Grazian, A., Fiore, F., & et al. 2015, A&A, in press (arXiv:1502.02562)
Gilli, R., Comastri, A., & Hasinger, G. 2007, A&A, 463, 79
Gilmore, R. C., Madau, P., Primack, J. R., Somerville, R. S., & Haardt, F. 2009, MNRAS, 399, 1694
Glikman, E., Djorgovski, S. G., Stern, D., et al. 2011, ApJ, 728, L26
Gnedin, N. Y. 2000, ApJ, 535, 530
Haardt, F. & Madau, P. 1996, ApJ, 461, 20
Haardt, F. & Madau, P. 2012, ApJ, 746, 125
Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, ApJS, 208, 19
Hiroi, K., Ueda, Y., Akiyama, M., & Watson, M. G. 2012, ApJ, 758, 49
Hopkins, P. F., Richards, G. T., & Hernquist, L. 2007, ApJ, 654, 731
Ikeda, H., Nagao, T., Matsuoka, K., et al. 2011, ApJ, 728, L25
Jarosik, N., Bennett, C. L., Dunkley, J., et al. 2011, ApJS, 192, 14
Lusso, E., Comastri, A., Vignali, C., et al. 2010, A&A, 512, A34
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Marchese, E., Della Ceca, R., Caccianiga, A., et al. 2012, A&A, 539, A48
Masters, D., Capak, P., Salvato, M., et al. 2012, ApJ, 755, 169
McQuinn, M. 2012, MNRAS, 426, 1349
Meiksin, A. 2005, MNRAS, 356, 596
Merloni, A., Bongiorno, A., Brusa, M., et al. 2014, MNRAS, 437, 3550
Miralda-Escude, J. & Ostriker, J. P. 1990, ApJ, 350, 1
Moretti, A., Vattakunnel, S., Tozzi, P., et al. 2012, A&A, 548, A87
Robertson, B. E. & Ellis, R. S. 2012, ApJ, 744, 95
Robertson, B. E., Ellis, R. S., Dunlop, J. S., McLure, R. J., & Stark, D. P. 2010, Nature, 468, 49
Salvaterra, R., Haardt, F., & Ferrara, A. 2005, MNRAS, 362, L50
Salvaterra, R., Haardt, F., & Volonteri, M. 2007, MNRAS, 374, 761
Salvaterra, R., Haardt, F., Volonteri, M., & Moretti, A. 2012, A&A, 545, L6
Schaye, J., Theuns, T., Rauch, M., Efstathiou, G., & Sargent, W. L. W. 2000, MNRAS, 318, 817
Silverman, J. D., Green, P. J., Barkhouse, W. A., et al. 2008, ApJ, 679, 118
Songaila, A. 2004, AJ, 127, 2598
Steffen, A. T., Strateva, I., Brandt, W. N., et al. 2006, AJ, 131, 2826
Telfer, R. C., Zheng, W., Kriss, G. A., & Davidsen, A. F. 2002, ApJ, 565, 773
Trac, H. & Cen, R. 2007, ApJ, 671, 1
Ueda, Y., Akiyama, M., Hasinger, G., Miyaji, T., & Watson, M. G. 2014, ApJ, 786, 104
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886
Vanden Berk, D. E., Richards, G. T., Bauer, A., et al. 2001, AJ, 122, 549
Vanzella, E., Siana, B., Cristiani, S., & Nonino, M. 2010, MNRAS, 404, 1672
Worseck, G., Prochaska, J. X., Hennawi, J. F., & McQuinn, M. 2014, ApJ, submitted (arXiv:1405.7405)
Wyithe, J. S. B. & Bolton, J. S. 2011, MNRAS, 412, 1926
Wyithe, J. S. B. & Loeb, A. 2003, ApJ, 586, 693
Xue, Y. Q., Luo, B., Brandt, W. N., et al. 2011, ApJS, 195, 10